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**SIMULATION OF RAYLEIGH-TAYLOR INSTABILITY GROWTH RATE
OF LASER ACCELERATED PLANE TARGET**

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INTRODUCTION

This report presents the research results for the time point when the Rayleigh-Taylor instability converts to the nonlinear stage as well as the computational results for the interaction of two modes of Rayleigh-Taylor instability when initial perturbations are concentrated at the ablation front (problem (a)) and on the rear side (problem (b)) of the plane target.

As was shown in the report for the first phase [1], for a target of 3 μm thick the existence time of the nonlinear stage is extremely low and does not allow to track the evolution pattern. In [1] it was shown that the plane target with $\Delta_0=5 \mu\text{m}$ is more preferable for this goal. Therefore all the computations presented here relate to the target with the indicated thickness. The laser pulse parameters are remained unchanged $J_L=10^{15} \text{ W/cm}^2$, $\lambda=0.35 \mu\text{m}$.

I. RESULTS OF 1-D COMPUTATIONS

We will begin by discussing the results of 1-D computations to the evolution changes in the instability patterns when the shell thickness was increase from 3 to 5 μm .

It is relatively clear that the characteristics of laser corona demonstrate a low sensitivity to the target thickness. This is seen in Fig. 1 which presents the temperature at the critical point as a function of time and dots correspond to the temperature values in the computations of the target 3 μm thick. However the target characteristics such as nonvaporized mass, velocity and acceleration changed considerably which can be easily seen from Fig. 2, 3. The effective thickness of the nonvaporized target portion in flight at $t=0.15 \text{ ns}$ is seen in Fig. 4. It is about 0.8 μm . Now we can evaluate the expected maximum value of the increment for this target using the formula (2.6) from [1].

This value occurs for k^* satisfying the relation $e^{-k^*\Delta} = 2b \frac{\sqrt{g\Delta}}{c_s} \sqrt{1 - e^{-k^*\Delta}}$. For $\Delta=0.8 \mu\text{m}$, $g \approx 2 \cdot 10^7 \text{ cm/c}^2$, $c_s=3 \cdot 10^7 \text{ cm/c}$ (see Fig. 1, 3 and 4) we obtain (the constant b in our estimation is taken to be 1):

$$k^* \approx 2 \cdot 10^4 \text{ cm}^{-1} \text{ and } \Gamma_{\max} \approx 33 \text{ ns}^{-1}.$$

The quasistationary profile forms by 0.08 ns and the target completely vaporizes by $\sim 0.25 \text{ ns}$. Thus the evolution of instabilities in computations can be tracked to $\sim 0.17 \text{ ns}$. During this period perturbation amplitude could increase by $e^{5.6} \approx 270$ times in linear regime of the instability. While we had $\Gamma t \approx 60 \cdot 0.04 \approx 2.4$ in the problem under consideration with 3 μm target. Hence the gain in the computational variation range of the instability amplitude is about 25 times when 5 μm target is used.

II. TIME OF INSTABILITY TRANSITION TO THE NONLINEAR MODE VERSUS INITIAL AMPLITUDE

In the evolution of Rayleigh-Taylor instability the initially specified perturbation mode progressively generates higher harmonics. In principle, there may exist multiple criteria for the evaluation of time point when the nonlinear mode emerges. This may be, for example, the time where the amplitude of the second harmonic reaches some portion of the amplitude of the first harmonic. We chose this fraction to be 20% which corresponds (as will be seen below) to the double increase in the amplitude of the second harmonics as compared to the mesh noise amplitude.

Fig. 1. Electron temperature at critical point versus time in 1-D computation for the plane targets with various thickness values.

Fig. 2. The change in nonvaporized target mass with time in 1-D computation for the targets with different initial thickness.

Fig. 3. Comparison velocities and accelerations of the nonvaporized target versus time in 1-D computations for 3 μm (curve with markers) and 5 μm initial thick targets.

Fig. 4. Density profile of the nonvaporized target at $t=0.15$ ns.

The dependence of interest can be evaluated from [2] for the infinitely thin shell.

For the constant acceleration, the general solution for the form of the shell in [2] is written as follows

$$x(\xi, t) = -\frac{gt^2}{2} + \sum_{s=1}^4 \sum_{n=1}^{\infty} A_{ns} \cos kn\xi e^{\Gamma_{ns}t} \quad (2.1)$$

$$y(\xi, t) = \xi + \sum_{s=1}^4 \sum_{n=1}^{\infty} B_{ns} \sin kn\xi e^{\Gamma_{ns}t} \quad (2.2)$$

here ξ is the Lagrangian coordinate along the shell, $\Gamma_{ns} = \sqrt{gkn}$ for $s=1,2$ ($B_{ns} = -A_{ns}$) and $\Gamma_{ns} = \pm i\sqrt{gkn}$ for $s=3,4$ ($B_{ns} = A_{ns}$) are the increments and eigenfrequencies of the perturbation with wave number k , g is the acceleration.

The application of the perturbation as a single mode with zero initial velocities (see formula (1.2) in [1] for $x=x_{\max}$) means the choice of A_{ns} and B_{ns} such that

$$\begin{aligned} x(\xi, t) &= -\frac{gt^2}{2} + \frac{A_0}{2}(\text{ch}\Gamma t - \cos\Gamma t)\cos k\xi \\ y(\xi, t) &= \xi - \frac{A_0}{2}(\text{ch}\Gamma t - \cos\Gamma t)\sin k\xi \end{aligned}$$

Now writing the plate shape as

$$x(y) = \sum_{k=1}^{\infty} C_n \cos kny$$

yields:

$$\begin{aligned} C_n &= \frac{2}{\pi} A_1(t) \int_0^{\pi} (1 - \beta_1(t) \cos z) \cdot \cos[n(1 - \beta_1(t) \sin z)] \cdot \cos z \, dz \\ A_1(t) &= \frac{A_0}{2}(\text{ch}\Gamma t + \cos\Gamma t), \quad \beta_1(t) = \frac{kA_0}{2}(\text{ch}\Gamma t - \cos\Gamma t) \end{aligned}$$

It is easily seen that the value of the second harmonic relation to the first one C_2/C_1 is the function of $\beta_1(t)$ only.

The ratio C_2/C_1 reaches the value 0.2 with $\beta_1=0.428$. Thus for the time t^* of transition to the nonlinear stage we obtain the equation:

$$2 \frac{0.428}{A_0 k} = \text{ch}\Gamma t^* - \cos\Gamma t^*.$$

The solution of this equation for $\Gamma=32 \text{ ns}^{-1}$ is given in Fig. 5.

For the evaluation of the dependence of interest, two series of computations were carried out where the perturbation wavelength was taken to be $4 \mu\text{m}$ (such that the instability increments are close to the maximum value).

The initial perturbations for problems (a) and (b) were introduced like in [1] (see formula (1.2)) except for that the time of perturbation introduction in problem (a) was $t_0=0.08 \text{ ns}$ instead of 0.06 ns .

Fig. 6 shows the evolution of the perturbation amplitude at the interface between nonvaporized target and laser corona¹ for problem (a) for two values of initial amplitude. It can be seen that for the time interval where the acceleration remains approximately the same (see Fig. 3), the increment is $\Gamma \approx 32 \text{ ns}^{-1}$.

Fig. 7 and 8 present the time dependence for the ratio of the second and first harmonics amplitudes for various values of initial perturbation amplitudes. In these figures the time is counted from the start of laser pulse while for the analysis of the transition time to nonlinear stage it is reasonable to consider the time period where the perturbation evolved. For problem (a) this means that the time should be counted from the introduction of the initial perturbation ($t_0=0.08 \text{ ns}$).

¹ A detailed definition of the interface is given in [1]. Here and further we will study the perturbation evolution at the interface as the most illustrative characteristic of 2-D flow.

Fig. 5 The time of Rayleigh-Taylor instability transition to nonlinear stage versus the amplitude of initial perturbations for the wavelength $\Lambda=4 \mu\text{m}$ for problems (a) - circles, and (b) - squares and theoretical estimation in the approximation of the infinitely thin plate (solid curve).

Fig. 6. The perturbation amplitude evolution at the interface of nonvaporized target and laser corona for various initial perturbation amplitudes at the ablation front at $t_0=0.08 \text{ ns}$ (problem (a)).

Fig. 7. Time dependence for the ratio of the second and first harmonics amplitudes for various initial perturbation amplitudes superimposed at the ablation front at $t_0=0.08$ ns (problem (a)).

Fig. 8. Time dependence for the ratio of the second and first harmonics amplitudes for various initial perturbation amplitudes superimposed at the rear side of the target at the initial time (problem (b)).

For problem (b), the time should be counted from the time where the perturbation from the rear side will be transferred by the rarefaction wave to the ablation front. Fig. 9 shows the evolution of the perturbation amplitude for problem (b) for various initial perturbation values. It is seen that for all amplitude values the perturbation arrival time to the ablation front is actually the same and corresponds $t_0=0.068$ ns.

In Fig. 5, the markers indicate the time of transition to the nonlinear stage versus the initial perturbation for problems (a) and (b). First, it is seen that in problems (a) and (b) the dependence of interest functionally is almost identical and the quantitative difference does not exceed ~ 20 ps.

Second, the approximation of thin shell reproduces the numerical results with a good accuracy.

Fig. 9. Time evolution of the perturbation amplitudes at the interface between the nonvaporized target and laser corona for various initial perturbation amplitudes superimposed at the rear side of the target at initial time in problem (b).

III. NONLINEAR INTERACTION OF MODES

To study the interaction of modes we chose the perturbation with the wavelengths $\Lambda=10 \mu\text{m}$ and $\Lambda=2 \mu\text{m}$. The wave numbers k of these perturbations are on different sides from k^* for which the maximum increments are achieved. This is convenient in terms of consistency between the growth rates of perturbation for selected modes to make them move synchronously through the linear and nonlinear stages.

Prior to the computations of two mode problem we studied the evolution of each mode independently.

Fig. 10 show the time evolution of perturbation amplitudes for both modes in problems (a) and (b). It is seen that for each mode the increments in problems (a) and (b) coincide and achieve $\Gamma_{10}=25 \text{ ns}^{-1}$ for $\Lambda=10 \mu\text{m}$ and $\Gamma_2=31 \text{ ns}^{-1}$ for $\Lambda=2 \mu\text{m}$.

Fig. 11 and 12 present the evolution of higher Fourier harmonics for the expansion of the interface shape for each mode in problems (a) and (b). What is striking is that for $\Lambda=2 \mu\text{m}$ the evolution of harmonics for (a) and (b) coincide qualitatively and quantitatively while for $\Lambda=10 \mu\text{m}$ the evolution of higher harmonics differs greatly in problems (a) and (b).

In [1] we have noted that for problem (b) the evolution of instabilities is considerably influenced by Richtmyer-Meshkov phase where the transversal velocity occurs when the shock arrives to the perturbed target rear side.

As is seen from [1] (see formula (1.2)), for $\Lambda=10 \mu\text{m}$ ($k\Delta\approx 3$) the perturbations applied to the rear side decrease towards the ablation front much more slowly than for $\Lambda=2 \mu\text{m}$ ($k\Delta\approx 15$). Therefore the mass involved in the motion in the transversal direction differs greatly for these two cases.

Fig.10. Time evolution of the perturbation amplitudes at the interface of the nonvaporized target and laser corona for two wavelengths of single perturbation modes superimposed at the ablation front (front) and on the rear of the target (back).

Fig.11. The amplitudes of higher harmonics in the Fourier transform of the perturbation shape of the interface between the nonvaporized target and laser corona versus the amplitude of the first harmonic for the perturbations with the wavelengths $\Lambda=2 \mu\text{m}$ in problems (a) and (b), respectively.

So one can expect that when the perturbation is transferred by the rarefaction wave to the ablation front, the transversal perturbation velocity will be much higher for $\Lambda=10 \mu\text{m}$ than for $\Lambda=2 \mu\text{m}$. The transversal velocity in the perturbation at the ablation front is just responsible for the behavior of higher harmonics in problems (a) and (b) for $\Lambda=10 \mu\text{m}$.

The same circumstance should lead to the difference in the evolution pattern of perturbations in two mode problem. We will illustrate our considerations as follows.

Fig.12. The amplitudes of higher harmonics in Fourier transform for the perturbation shape of the interface between the nonvaporized target and laser corona versus the amplitude of the first harmonic for the wavelength $\Lambda=10 \mu\text{m}$ in problems (a) and (b), respectively.

For the infinitely thin plate, the perturbations containing two modes with nonzero transversal velocity have the form (see (2.1), (2.2)):

$$x(\xi, t) = \frac{A_1}{2} (\text{ch } \Gamma_1 t + \cos \Gamma_1 t) \cdot \cos k\xi + \frac{A_5}{2} (\text{ch } \Gamma_5 t + \cos \Gamma_5 t) \cdot \cos 5k\xi + \frac{\beta_1}{2} (\text{sh } \Gamma_1 t - \sin \Gamma_1 t) \cdot \cos k\xi + \frac{\beta_5}{2} (\text{sh } \Gamma_5 t - \sin \Gamma_5 t) \cdot \cos 5k\xi \quad (3.1)$$

$$y(\xi, t) = \xi - \frac{A_1}{2} (\text{ch } \Gamma_1 t - \cos \Gamma_1 t) \cdot \sin k\xi - \frac{A_5}{2} (\text{ch } \Gamma_5 t - \cos \Gamma_5 t) \cdot \sin 5k\xi - \frac{\beta_1}{2} (\text{sh } \Gamma_1 t + \sin \Gamma_1 t) \cdot \sin k\xi - \frac{\beta_5}{2} (\text{sh } \Gamma_5 t + \sin \Gamma_5 t) \cdot \sin 5k\xi \quad (3.2)$$

where A_1 and A_5 are the initial perturbation amplitudes for the modes with $\Lambda=10 \mu\text{m}$ and $\Lambda=2 \mu\text{m}$, respectively and $\beta_1=v_1/\Gamma_1$, $\beta_5=v_5/\Gamma_5$ where v_1 and v_5 are the transversal velocities respective modes.

To study the interaction of modes, we choose the initial amplitude of the first harmonic, with somewhat lower increment, is greater and has another sign as compared to the initial amplitude of the fifth harmonic: $A_1 \cdot k \approx 0.13$ and $5k \cdot A_5 \approx -0.1$. Thus the fifth harmonic evolving from the perturbation with the wavelength $\Lambda=10 \mu\text{m}$ (see Fig. 12) will be on one hand in the counter phase relative to the initial perturbation with $\Lambda=2 \mu\text{m}$ and on the other hand their amplitudes in the linear stage will be comparable. This would allow to avoid too early jet formation in the short wave mode and to track the interaction for a longer time. In problem (a) the transversal velocity of perturbation does not exist. Fig. 13 presents the shape of plate given by formulas (3.1), (3.2) at $\Gamma_1 t = 2.2$ when (3.1), (3.2) are still single-valued (do not form a loop).

In problem (b) we can evaluate the value of v_1 as follows. When the shock wave arrives to the rear side of the target, the maximum value of the transversal velocity is $v_0 = \frac{2}{\gamma-1} c \cdot A_1 k$

where $c = D \frac{\sqrt{2\gamma(\gamma-1)}}{\gamma+1}$ is the sound speed behind the shock wave moving with the velocity D .

In our problem $D \approx 10^7$ cm/s. So that $v_0 \approx 1.7 \cdot 10^6$ cm/s² with $\gamma = 5/3$. The values $v_{1,5}$ from $\beta_{1,5}$ are in fact determined by the average mass velocity along the plate which is related to v_0 by
$$\bar{v} = \frac{1}{\Delta} \int_0^\Delta u_0 \exp(-kx) dx = \frac{v_0}{k\Delta} (1 - e^{-k\Delta}).$$
 Here k is the wave number of the corresponding mode and Δ is the plate thickness. Thus we obtain the following estimate: $v_1 = 6 \cdot 10^5$ cm/s for $\Delta = 10 \mu\text{m}$ and $v_5 = 1.2 \cdot 10^5 < v_1$ for $\Delta = 2 \mu\text{m}$.

Fig. 14 presents the plate shape given to moment of the loss of single-valued pattern.

By comparing Figs. 13 and 14 one can be easily seen the qualitative difference in the evolution of two mode perturbations for problems (a) and (b).

We computed the evolution of two mode perturbations with the initial amplitudes of the modes mentioned above ($k \cdot A_1 = 0.13$ for $\Delta = 10 \mu\text{m}$, $5k \cdot A_5 = -0.1$ for $\Delta = 2 \mu\text{m}$) with MIMOZA code.

It is important to note that the computations were run with Lagrangian code without mesh reconfiguration till the target burn through corresponding to the completion of computations.

Figs. 15-17 show 2-D density distributions from problems (a) and (b) at various times. For illustration Fig. 18 presents the fragments of meshes at various times. It is seen that in the nonlinear phase the plate shapes in problems (a) and (b) greatly differ while the difference pattern qualitatively agrees for the infinitely thin plate shown in Figs. 13, 14. This confirms our statement that the source of difference is Richtmyer-Meshkov stage generating the perturbation with the transversal velocity in problem (b). An additional illustration of the evolution of nonlinear interaction between the modes in problems (a) and (b) is represented by Figs. 19-20 showing the evolution of higher harmonics of the ablation front shape. It is seen that the composition and time evolution of harmonics in problems (a) and (b) qualitatively differ.

CONCLUSIONS

1. The studies were performed of how the time of Rayleigh-Taylor instability transition to the nonlinear phase depends on the initial amplitude. It was shown that the approximation of infinitely thin shell describes well the 2-D results both for the perturbations applied to the ablation front and to the rear side.

2. The computations were run for the evolution of two-mode perturbations with the wave lengths $\Delta = 10 \mu\text{m}$ and $\Delta = 2 \mu\text{m}$. The MIMOZA code allows to track the interaction of modes in the deep nonlinear phase.

It is indicated that the interaction of two modes qualitatively differs when the perturbation are applied to the ablation front and to the rear side of target.

It was demonstrated that the main source of this difference is Richtmyer-Meshkov instability generating transversal velocity perturbations when the shock wave arrives to the rear side of the plate.

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Fig. 13. Surface shape of the infinitely thin plate at $\Gamma_1 t = 2.2$ in the case where no transversal velocity exists in the initial perturbations representing the sum of the first and fifth harmonics.

Fig. 14. Surface shape of the infinitely thin plate at $\Gamma_1 t = 2.2$ when the transversal velocities $v_1 = 6 \cdot 10^5$ cm/s and $v_2 = 0$ are specified for initial perturbations representative the sum of the first and fifth harmonics.

a)

b)

Fig. 15. Density distributions at $t=0.1$ ns in the computations of evolution of two-mode perturbation applied to the ablation front (a) and to the rear side (b).

a)

b)

Fig. 16. Density distributions at $t=0.18$ ns in the computations of evolution of two-mode perturbation applied to the ablation front (a) and to the rear side (b).

a)

b)

Fig. 17. Density distributions at $t=0.21$ ns and 0.225 ns correspondingly in the computations of evolution of two-mode perturbation applied to the ablation front (a) and to the rear side (b).

Fig. 18. Fragments of the computational meshes at various times in two-mode perturbations evolution calculation in problem (a).

Fig.19. Evolution of amplitudes of various harmonics in Fourier transform of the interface shape in problem (a) when the two-mode perturbation is applied to the ablation front at $t_0=0.08$ ns.

Fig. 20. Evolution of amplitudes of various harmonics in Fourier transform of the interface shape in problem (b) when the two-mode perturbation is applied to the target rear side at initial time.

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**INVESTIGATION OF EVOLUTION OF INTERFACE
AFTER ITS INTERACTION WITH SHOCK WAVES**

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ABSTRACT

The present report is performed according to the plan of the first stage of the contract C 500500015-35 between the University of California (LANL) and the International Institute for Applied Physics and High Technology.

The report includes:

- Description of the experimental set-up;
- Procedures of visualization of the process, including the "method of grid" applied in order to obtain the images of the object of the study with more definite boundaries between the zones than in previous experiments. The experiments were performed on the modified set-up, that allowed us to obtain the object images with higher resolution;
- Analysis of the errors of measurement of the basic characteristics of the process;
- Results of the investigation of the main types of the evolution of the interface between gases of different densities on the shock passage through it. We considered the passages of the incident shock from heavy to light gas and from light to heavy gas through the two-dimensional initial interface modeled by a thin film;
- Preliminary data on the study of the interface evolution induced by the incident shock after the passage of reflected shocks through the interface.

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1. DENOTATIONS

Elements of the setup:

D_1 — the driver section of the shock tube

D_2 — the driven section of the shock tube

D_0 — the diaphragm

TS — test section

K_0 — the initial interface

CFV — the center of the field of view

a_0, λ, k — amplitude, wavelength and wave number of the initial interface K_0

EW — the end wall of the shock tube

OKM-2M, OKM-4, OKM-5 — test sections

Elements and parameters of the process:

A & B — disposition of the gases (to the right and to the left of the initial interface, respectively)

S_{e1a} — the incident shock

S_{i1b} — the refracted shock in gas B (after the interaction of S_{e1a} with K_0)

S_{i1a} — the reflected shock in gas A (after the interaction of S_{e1a} with K_0)

K_{12} — the interface between the shocked flows $i1b$ and $i1a$

S_{e2b} — the reflected shock in gas B moving from the end wall of the shock tube toward K_{12}

S_{i2a} — the refracted shock propagating in gas A (after the interaction of S_{e2b} with K_{12})

S_{i2b} — the reflected shock moving in gas B to the end wall (after the interaction of S_{e2b} with K_{12})

K_{23} — the interface between the shocked flows $i2b$ and $i2a$

S_{e3b} — the reflected shock moving in gas B from the end wall of the shock tube toward K_{23}

W_{ijk} — velocity of S_{ijk}

M_{ijk} — Mach number of S_{ijk}

U_{ijk} , ρ_{ijk} , P_{ijk} , T_{ijk} — velocity, density, pressure, temperature of the flow behind S_{ijk}
 P_0 and ρ_0 — the initial pressure and density

$At = (\rho_2 - \rho_1)(\rho_2 + \rho_1)^{-1}$ — the Atwood number, where ρ_1 and ρ_2 — the densities of gases A and B, respectively

K^1 , K^3 , K^5 — the characteristic points of K_{ij} on the end wall side

K^2 , K^4 , K^6 — the characteristic points of K_{ij} on the driver section side

X_{ijk}^n , — coordinates of characteristic points of K_{ij} , $n = 1, 2, \dots, 6$

S^1 , S^2 — characteristic points of S_{ijk}

a_s — the amplitude of S_{ijk}

a_{ijk} — the amplitude of K_{ij}

Δ_{ij} — thickness of K_{ij}

d_1 — width of the mushroom stem

d_2 — width of the mushroom

h — height of the mushroom

$$X_{ijk}^{1-2} = 0.5(X_{ijk}^1 + X_{ijk}^2)$$

$$X_{ijk}^{3-4} = 0.5(X_{ijk}^3 + X_{ijk}^4)$$

$$X_{ijk}^{5-6} = 0.5(X_{ijk}^5 + X_{ijk}^6)$$

$$\overline{X}_{ijk}^4 = 0.5(X_{ijk}^4 + X_{ijk}^6)$$

$$\overline{X}_{ijk}^1 = 0.5(X_{ijk}^1 + X_{ijk}^5)$$

Fig. 1.1. Scheme of the experimental set-up and the x - t diagram of the process.

Fig. 1.2. Schemes of test sections. 1) Test section OKM-5; 2) test section OKM-4; 3) test section OKM-2M; 4) the test section OKM-4 including the end of the shock tube (for experiments with the reflected shock wave).

2. INTRODUCTION

For investigating the Richtmyer-Meshkov Instability (RMI), the relation suggested by Richtmyer is often used (Richtmyer, 1960):

$$\frac{da_K}{dt} = a_K^* U k A t \quad (1)$$

This relation is applicable for the shock passage from light to heavy gas through the two-dimensional (2D) sinusoidal interface with the amplitude a_0 and the wave number k . Here $a_K(t)$ is the current amplitude of the interface after the end of refraction, $At = (\rho_2 - \rho_1)(\rho_2 + \rho_1)^{-1}$ is the Atwood number, U is the velocity of the interface. The zone of applicability of (1) is limited by the small Mach numbers M_0 of the incident shock wave, the small curvature of the initial interface ($a_0 k \ll 1$) and the small At values.

Meshkov has shown in experiment (1969) that this instability is induced on both the passages of the incident shock wave, from light to heavy gas and from heavy to light gas. It has been shown that for $a_0 k < 1$ and $M_0 < 1.6$ at the initial stage of interface evolution, the amplitude a_K grows linearly in time. For the shock passage from light to heavy gas, the relation (1) satisfactorily describes the results of experiment.

Meyer and Blewett (1972) made an attempt to apply the relation (1) for the shock passage from heavy to light gas by replacing a^* with $0.5(a^* + a_0)$.

The numerical and experimental studies on RMI performed for the passage of the shock from light to heavy gas through 2D sinusoidal interface (Aleshin et al., 1990; Zaytsev et al., 1991; Aleshin et al., 1990), have shown the following.

1. The interface evolution after the end of refraction develops through the number of characteristic stages of which the final one is the formation of the turbulent mixing zone of thickness L .
2. The increase of $a_0 k$ accelerates the development of the evolution to the turbulent stage.
3. The dL/dt value is slightly affected by $a_0 k$.

4. The properties of the interface evolution after the end of refraction are dependent on the character of the refraction of the incident shock wave on initial interface.

Note that the passage of the incident shock through 2D sinusoidal interface is accompanied by formation of the refracted and reflected shocks ($\rho_1 < \rho_2$). The non-uniform pressure distribution that arises behind the refracted and reflected shocks, determines the RMI evolution. The pressure amplitude $P_{\max}$ for this distribution depends on $a_0 k$, M_0 and At .

Analysis of the regimes of the incident shock refraction on 2D sinusoidal initial interface allowed us to distinguish three regimes of the RMI evolution for $\rho_1 < \rho_2$.

1. Soft regime. In this case, four characteristic stages of the RMI evolution are observed after the end of refraction.

Linear stage ($a_K < 0.4\lambda$). The a_K grows linearly in time according to the relation (1). The interface retains sinusoidal shape.

Non-linear stage ($0.4\lambda < a_K < 0.7\lambda$). The shape of interface undergoes the characteristic distortion: the heavy gas penetrates in the light gas as tapering spikes, and the light gas penetrates into the heavy gas as growing bubbles.

Transitional stage ($0.7\lambda < a_K < 1.5 - 2\lambda$). The vortex structures of characteristic mushroom shape are generated on the spike tip. During the motion, the vortex structure grows in size.

Turbulent stage (the final one) is characterized by the interaction of the adjacent vortex structures.

The rate of penetration of one gas into the other determined by the da_K/dt , decreases on the transition from each preceding stage to the following one.

2. Hard regime. After the end of refraction, the RMI evolution includes three stages: non-linear, transitional, and turbulent. This regime is characterized by the generation of the secondary shocks in the flow between the refracted and reflected shocks.

3. Irregular regime. After the end of refraction, the RMI evolution includes two stages: transitional and turbulent.

It is necessary to especially underline the following. For the regular regimes (soft and hard), formation of the mushroom structures is due to the shear instability of Kelvin-Helmholtz. For irregular regime, the mushroom structures are forming during the refraction on the interface, thus indicating the non-evolutionary character of the process.

The time of achieving the turbulent stage is reduced for hard versus soft regime, and for irregular versus hard regime, so for the same initial M_0 , At and a_0 the depths of penetration on the turbulent stages for these regimes are reduced, respectively.

The problem of creating an adequate descriptive model for the passage of the incident shock wave through an interface comes to determining the depth of penetration of one medium into the other, depending on the a_0k , M_0 and At .

Another problem of the RMI is the description of the evolution of the interface after the reflected shock passage through it. It should be noted that in experiments performed in shock tubes, by the moment of collision of the reflected shock with the interface, the latter is a layer of finite thickness Δ with continuous density distribution. The use of continuous instead of discontinuous interface results in reduction of the growth rate $a_K(t)$ (Zaytsev et al., 1993). The correct account for this effect for the regimes realized for the interaction of the interface with the reflected shock, requires further investigation.

The effect of the evolution of the interface before the collision with the reflected shock on that after the collision is probably due at least to the following. First, it is the growth of the interface amplitude before the interaction with the reflected shock. Second, it is the fact that the interface is a layer of finite thickness.

For the $\left[\frac{da_K}{dt}\right]_i$ (after i collisions with the reflected shock), Brouillette and

Sturtevant (1990) suggested the following relation:

$$\left[\frac{da_K}{dt}\right]_i = \sum_0^i \frac{(a_K^*)_j k U_j At}{\psi_j}, \quad (2)$$

where $\psi_j = \psi_j(\Delta, k, At)$.

The direct experimental testing of the relation (2) requires to provide the soft regime of refraction for all the shock interactions with the interface, and this meets

certain difficulties. It is also necessary to study in experiment the interaction of the interface with the reflected shocks for the hard and irregular regimes. The need of these studies is due to the necessity of description of the RMI evolution in the layers with alternating density.

Below, we give the description of the experimental set-up intended to investigate the indicated problems. We present the data on the study of different regimes of the RMI evolution for the passages of the incident shock from light to heavy gas or vice versa through 2D sinusoidal interface, and the data on the interface evolution after the interaction with the reflected shock wave.

3. EXPERIMENTAL SET-UP

The experiments were performed in a shock tube (for the scheme, see Fig. 3.1). The driver was a 1000 mm tube of round cross-section with 20 mm thick walls and the inner diameter of 100 mm. The oxygen-hydrogen-helium mixture (O_2+2H_2+7He) at the pressure 2.6 atm was used as the pusher. The mixture was ignited with the current-heated Ni-Cr alloy filament stretched along the driver. This method of ignition allows to obtain the uniformity of the flow behind the front of the incident shock wave.

The driven channel was of square section ($72 \times 72 \text{ mm}^2$). The driven was assembled of 8 similar sections, each 450 mm long, and one transitional section to provide the smooth junction between the driven ($72 \times 72 \text{ mm}^2$) and the driver ($\varnothing 100 \text{ mm}$). The diaphragm D_0 placed between the driver and the driven was the 0.9 mm copper plate with the 0.6 mm cross-shaped notch on the driven side. The driven was equipped with three contact gauges D_1 , D_2 , and D_3 to measure the velocity of the incident shock.

The test section TS attached to the end of the driven is destined for investigating the RMI. Within the section, a thin lavsan film K_0 was installed to model the initial 2D sinusoidal interface. The process was visualized downstream from the place of the film fastening. Fig. 1.2 shows the scheme of the film disposition and the system of coordinates used in the study. The zero section is matched with the plane of the film fastening on the top and bottom walls of the driven, the positive direction of the X axis runs downstream. The number of test sections allows us to visualize the process in the following sections: $3.5 \text{ mm} < X < 113.5 \text{ mm}$ (TS OKM-5), $28 \text{ mm} < X < 172 \text{ mm}$ (TS OKM-4), and $133 \text{ mm} < X < 277 \text{ mm}$ (TS OKM-2M). The design of the set-up provides the vacuum-tight separation of the driven volumes on both sides of the film K_0 . When performing the present contract, we modified the test sections OKM-4 and OKM-5 that allowed us to increase the amplitude of the initial interface up to 30 mm (versus 10 mm maximum amplitude in previous experiments).

The experimental set-up is equipped with the evacuation system and the system of filling with working gases. Prior to experiment, the set-up was evacuated

to 10^{-1} torr, then both parts of the driven were filled with working gases to 0.5 atm, providing that the pressure differential on different sides of the film K_0 did not exceed 0.2 torr, because the larger differentials led to irreversible deformation of the initial interface. The inleakage for each driven volume did not exceed 10^{-2} torr/min.

The process was visualized by the Schlieren method with the device IAB-451. The process was recorded with a high speed photographic camera ZhFR-3. The light source was a ruby laser with a passive shutter allowing us to obtain 12-18 light pulses of 10^{-1} μ s. The time interval between two pulses was varied within 10-25 μ s range. As the visualizing diaphragms we used the couple consisting of the entrance diaphragm (aperture of $\varnothing$ 2.5 mm) and the exit diaphragm (sphere of $\varnothing$ 2.5 mm). In addition, to increase the sharpness of Schlieren pictures and the resolution, we also used the "method of grid" described below.

Fig. 3.1. Scheme of the experimental set-up. 1) Test section; 2) driven; 3) driver; 4) ZhFR-3; 5) system of evacuation and filling with working gases; 6) system for measuring the velocity of shock; 7) light source; 8) system of control and synchronization; 9,10) the device IAB-451.

4. VISUALIZATION BY THE "METHOD OF GRID"

To increase the resolution of Schlieren pictures, we applied the "method of grid" developed on the basis of the procedures of "defocused grid" and "inclined defocused thread" (Skotnikov, 1976; Vasilyev, 1968).

The evolution of RMI is characterized by large density gradients and, respectively, the large deflections of the exploring beams. The device IAB-451 records only the deflections not exceeding 8×10^{-4} radn (the dynamic range of the device). When heavy gases (Kr, Xe) are used in experiments at the initial pressure 0.5 at and the Mach number of the incident shock wave ranged 2.5-4.5, the perturbations arising in the supersonic flow (at the chamber joints, etc.) cause the deflections of the exploring light beam comparable with the dynamic range of the IAB-451 device.

The gas-dynamic objects with large gradients of the refractive index are better recorded by the shadow method, however, in this case the image of the object is defocused. This reduces the accuracy of measuring the sizes of the gas-dynamic structures on the object.

The "method of grid" is an attempt to join the advantages of the Schlieren method (the sharpness of the object images) and the shadow method (the sharpness of the images of the gas-dynamic structures with large gradients of the refractive index).

Figure 4.1 shows a part of the optical scheme of the visualization system. Parallel light beam passes through the visualization field, undergoes distortion and enters the receiver of the IAB device with lens of $\varnothing$ 230 mm and 1917 mm focal length. After the mirror 1*, the light beam passes through the visualizing diaphragm 2. The diaphragm 2 is a $\varnothing$ 2.5 mm sphere (for Schlieren method) or a $\varnothing$ 20 mm aperture matched by the size with the mirror 1*. The location of the diaphragm 2 is the place of the light source focusing. The light beam passed through the lens 3 ($F = 210$ mm) forms the first object image in the zone 4. After passing through the lens 5 ($F = 210$ mm), the beam is reflected from the pivoted polyhedron 6 of the high speed camera ZhFR-3 and forms the object image which is recorded on the film 7.

In the methods of "defocused grid" or "inclined defocused thread", the additional visualization diaphragm is the system of threads placed between the diaphragm 2 and the lens 3, and the light source is a slit. This method is characterized by the small dynamic range, and only the one-direction refractive index gradients are recorded well.

In the "method of grid", the light source is a $\varnothing$ 2.5 mm aperture, and the additional diaphragm is placed after the lens 3, but before the lens 5. The additional diaphragm can be placed before or behind the zone 4. Figure 4.2 shows the pictures obtained by different methods for one regime: a) using the Schlieren method with the aperture-sphere diaphragm system; b) using the "method of grid". Figures 4.2, c and d correspond to the "method of grid", but in these cases the additional diaphragm is placed after the first object image. As seen, the use of the "method of grid" allowed us to significantly increase the sharpness of the images of the refracted shock S_{ilb} , secondary shocks, and the contrast range of the images of K_{12} and the gas flow between S_{ilb} and K_{12} .

Fig.4.1. Optical scheme of visualization by the "method of grid".

- 1) The receiver of the device IAB-451; 1*) the mirror of the device IAB-451;
- 2) visualizing diaphragm; 3,5) lenses I-51 ($F=210$ mm); 4) the location of the image of visualized object; 6) the pivoted mirror polyhedron of the high speed camera ZhFR-3; 7) the film of the camera;
- 8) the visualized object; Δ_1 and Δ_2 are the defocusing distances.

a.

b.

c.

d.

Fig. 4.2. Schlieren pictures of the shock passage from He into Xe through the 2D perturbation ($\lambda=72$ mm, $a_0=10$ mm). a) standard shadow method; b) "method of grid"; $\Delta_1=26$ mm, grid spacing is 2 mm; c) "method of grid"; $\Delta_2=50$ mm, grid spacing is 1.7 mm; d) "method of grid"; $\Delta_2=25$ mm, grid spacing is 0.85 mm.

5. ANALYSIS OF EXPERIMENTAL ERRORS

The error of each run was determined by the following components:

- the errors of instrumentation appeared during the performance of experiment (when determining the shock velocity and the time intervals between the frames for recording the process with high speed camera);
- the errors of making the framework onto which the film was glued to model the initial interface;
- the error due to the variations in the shape of initial interface;
- the errors of measurement during the processing of the data (the errors of determining the disposition of characteristic lines in Schlieren pictures).

Let us consider every component in more details.

Velocity of the incident shock S_{e1a} was measured using the base method by the time interval between the signal coming from the contact gauges, at the shock passing by each of them. The gauges with the receiving surface of $\varnothing 2.5$ mm were 240 mm distant one from another. The error of measurement of the velocity of the incident shock was about 2%. Within the visualization field, the design of the shock tube provides the constant velocity of the incident shock for the heavy gases (Ar, Kr, Xe) and the accelerated shock motion for He. This acceleration measured independently in two bases increased the shock velocity within the visualization field by no more than 4% for 1 m of the passed distance.

The error of making the framework for the initial interface was defined as $+0.1/-0.3$ mm by amplitude and ± 1 mm by wavelength. In experiments we used the frameworks with the perturbation amplitude $a_0 = 5, 10, 20$, and 30 mm. The errors for the indicated a_0 were 8, 4, 2, and 1.5%, respectively. We used the wavelengths λ of 36 and 72 mm. The errors of making the framework were 3% for the amplitude and 15% for the wavelength.

The much more significant contribution to the experimental error is the error due to the variations in the shape of initial interface. During the evacuation of the driven and its filling with the working gases, there may appear the non-controllable perturbations with the characteristic parameters ($a < 5$ mm and $\lambda < 5$ mm) on the surface of the film glued onto the framework. Normally they appear for $a_0/\lambda < 0.4$.

The account for these additional errors results in the following total errors of determination of the initial perturbation: 18, 9, 4.5, and 3.5% for the initial amplitudes $a_0 = 5, 10, 20,$ and 30 mm, respectively.

The errors appearing during the processing of Schlieren pictures are mainly due to the subjective operator's estimation of the observed picture. The resolution of the microscope used for measurements is no lower than $2\text{ }\mu\text{m}$. The scale of the image in the frame was about 0.14 of the real one. Thus, the instrumental error for the measurement in real scale did not exceed $15\text{ }\mu\text{m}$. The errors due to the subjective operator's estimation when measuring the objects with sharp boundaries (frame boundaries, shock waves) or less clear boundaries (interface shapes), were 0.1 or 0.7 mm by absolute value in real scale, respectively. This error of measurement provides the $0.1\text{ }\mu\text{s}$ accuracy for determination of time intervals and no lower than 5% accuracy for the determination of the shock velocities. For the Ar-Ar couple, the difference between the shock velocities measured by the base method and those obtained by the direct measurement of the distance between the frames on photographic film is less than 1%, that is significantly lower than the accuracy of the velocity measurement by the each method.

The accuracy of determination of the interface amplitudes $a_{K12}(t)$ for a single interaction with the shock is 10-14% for $a_{K12}(t) < 5$ and about 1.5 mm by the absolute value for the large $a_{K12}(t)$ values. The growth rate of perturbation is determined with no less than 15% accuracy.

The error of determination of the amplitude $a_{K23}(t)$ of the interface after the interaction with the reflected shock is higher. The increased variation is mainly due to the intensive growth of perturbations caused by the non-controllable distortions of the shape of initial interface and the excitation of the turbulence. This decreases the contrast of the images of the fronts between the K_{23} and "pure" gases. In addition, the number of experimental points on this stage of the RMI evolution normally does not exceed 3-5. The measurements by the operators may vary by more than 1 mm by absolute value, and the error of determination of the perturbation growth rate $da_{K23}(t)/dt$ is not less than 25-30%.

6. REGIMES OF EXPERIMENT

In the present study we used the initial pressures P_0 of gases, Mach numbers M_0 of the incident shock wave, and the films modeling the initial interface which allowed us to ignore the effect of the film on the character of the process evolution. The experiments were performed with 2 μm (approx.) lamsan films of running density $4.2 \times 10^{-4} \text{ g/cm}^3$. The initial pressure of working gases (He, Ar, Kr, and Xe) was 0.5 atm. We used the shocks with Mach numbers ranged 2.5-4.5.

It has been shown that for the indicated regimes, the x-t diagrams of the passages of planar shock waves through the plane films between the above-listed gases coincide with the calculated ones within the experimental error. The calculated data were obtained by the numerical solution of the one-dimensional problem of the interaction of planar shock with a plane interface. It has been found that the shock ($M_0 > 2.5$) passage through the thin film of curvilinear shape, provided that there is the same gas on both sides of the film, results in formation of the optical non-uniformity moving at the velocity of the shocked gas. The traveling of the small perturbation waves and the shock waves through this non-uniformity affect neither their velocity, nor their shape.

To obtain the quantitative information on the evolution of all the regimes of RMI evolution induced by the interaction of the incident shock wave with the 2D sinusoidal initial interface, we performed the experiments, the regimes of which are given in Table 7.1. The regimes of experiments performed for investigating the RMI evolution induced by the reflected shock wave, are also given in Table 7.1.

TABLE 7.1. Initial and experimental data on all the experiments included in the report.

Initial data								Estimated data		Experimental data					
No.	A→B	At	test section	λ mm	a_0 mm	W_{ela}	M_{ela}	W_{ilb}^*	U_{K12}^*	W_{ilb}^1	W_{ilb}^2	U_{K12}^1	U_{K12}^4	da/dt	da/dS
635B	Kr→Xe	0.182	OKM-5	36	30	0.823	3.74	0.725	0.512	0.720	0.765	0.557	0.503	0.013	0.026
636B	Kr→Xe	0.182	OKM-5	36	30	0.827	3.76	0.725	0.515	0.708	0.731	0.526	0.462	0.058	0.111
627B	Ar→Kr	0.29	OKM-5	36	10	1.170	3.67	0.945	0.670	0.930		0.693	0.574	0.119	0.172
620B	Ar→Kr	0.29	OKM-4	36	10	1.111	3.48	0.894	0.630	0.917		0.628	0.566	0.055	0.089
646B	Ar→Kr	0.29	OKM-2M	36	10	1.136	3.56	0.916	0.647	0.897		0.636	0.620	0.016	0.025
628B	Xe→Ar	0.45	OKM-5	36	5	0.861	4.92	1.155	0.801	1.104	1.094	0.810	0.725	0.078	0.096
631B	Xe→Ar	0.45	OKM-5	36	5	0.783	4.47	1.058	0.721	1.041	1.051	0.770	0.682	0.077	0.099
629B	Xe→Ar	0.45	OKM-5	36	10	0.822	4.7	1.107	0.761	1.032	1.016	0.830	0.662	0.156	0.187
630B	Xe→Ar	0.45	OKM-5	36	20	0.788	4.5	1.064	0.726	1.010	1.028	0.846	0.635	0.229	0.271
632B	Xe→Ar	0.45	OKM-5	36	30	0.799	4.57	1.079	0.738	1.004	1.012	0.860	0.601	0.256	0.298
622B	He→Xe	0.915	OKM-5	36	10	2.903	2.88	0.845	0.606	0.832		0.593	0.382	0.211	0.356
619B	He→Xe	0.915	OKM-4	36	10	2.832	2.81	0.820	0.586	0.877		0.621	0.451	0.173	0.278
633B	He→Xe	0.915	OKM-5	36	20	2.910	2.89	0.849	0.609	0.865	0.945	0.650	0.406	0.301	0.471
637B	He→Xe	0.915	OKM-4	36	20	2.766	2.75	0.798	0.569	0.847	0.855	0.624	0.448	0.174	0.28
634B	He→Xe	0.915	OKM-5	36	30	2.797	2.78	0.809	0.577	0.800	0.910	0.596	0.406	0.158	0.28
Experiments with the end wall															
638B	Xe→He	0.91	OKM-4	36	5	0.887	5.07	2.021	1.139	1.906		1.175	1.045	0.130	0.114
639B	Xe→Ar	0.45	OKM-4	36	5	0.842	4.81	1.131	0.781	1.147		0.835	0.755	0.080	0.103
640B	Xe→Kr	0.182	OKM-4	36	5	0.707	4.04	0.800	0.554	0.797		0.561	0.529	0.023	0.041
641B	Xe→Kr	0.182	OKM-4	36	5	0.697	3.98	0.788	0.545			0.572	0.550	0.028	0.051
592B	Xe→Kr	0.182	OKM-4	36	5	0.681	3.89	0.771	0.53	0.743		0.539	0.498	0.028	0.052

7. RESULTS OF EXPERIMENTS

7.1. Evolution of K_{12} .

Table 7.1 gives the initial data, the estimated data on the interaction of the incident shock wave S_{e1a} with the plane interface K_{12} , and the experimental data.

Initial data. The column "A→B" shows the direction of the S_{e1a} passage. "Ar" is the Atwood number of the contacting gases. The column "Chamber" shows the type of the used test-section. The visualization fields for each test-section are shown in Fig. 1.2. λ and a_0 are the wavelength and the amplitude of K_0 , respectively. W_{e1a} and M_{e1a} are the velocity and the Mach number of the shock S_{e1a} traveling in gas A.

Estimated data. W_{i1b}^* and U_{K12}^* are the velocities of the refracted shock S_{i1b} and the plane interface between the shocked flows generated by S_{i1b} and S_{e1a} . W_{i1b}^* and U_{K12}^* are obtained by numerical solution of the conservation equations describing the interaction of the planar incident shock with the plane interface. a_{K12}^* is the estimated value of the K_{12} at the end of refraction of the incident shock wave on the 2D sinusoidal interface:

$$a_{K12}^* = a_0 \left(1 - \frac{U_{12}}{W_{e1a}} \right).$$

Experimental data. W_{i1b}^1 and W_{i1b}^2 are the velocities of the characteristic points of the refracted shock S_{i1b} ; U_{K12}^1 and U_{K12}^4 are the velocities of the characteristic points of K_{12} . The disposition of these points on K_{12} and S_{i1b} is given in Figs. 7.1 and 7.2. da_{K12}/dt is the mean growth rate of the K_{12} amplitude within the visualization field.

Schlieren pictures of the performed experiments on the 1:2 scale are given in Appendix 1. The x-t diagrams of the motion of the characteristic points of K_{12} and S_{i1b} are given in Appendix 2. The trajectories S_{i1b}^1 and S_{i1b}^2 correspond to the extremum points of the reflected shock front.

Fig. 7.1. Designation of characteristic points on K_{12} (A - Run No. 631B frame No. 7) and S_{11b} (B - Run No. 634B, frame No. 6). Test section OKM-5. CFV is the center of the field of view (see Fig. 1.2.).

Fig. 7.2. Designation of characteristic points on K_{12} .
Run No. 619B, frame No. 6. Test section OKM-4. CFV is the center of the field of view (see Fig. 1.2.).

Fig. 7.3. The non-dimensional amplitude $\overline{a_{K12}}$ of the interface K_{12} versus the non-dimensional distance $\overline{X_{K12}}$ passed by K_{12} .

The interaction of the S_{e1a} with the K_0 modeled by the thin film results in formation of the interface K_{12} recorded as the 2D layer of finite thickness Δ . The boundaries between this layer and the shocked flows of the "pure" gases are not sufficiently contrast. This fact, as already mentioned, results in the errors in measuring the coordinates of the characteristic points and the perturbation amplitude a_{K12} of K_{12} .

Appendix 3 gives the numbers of frames and the corresponding time intervals, as well as the measured coordinates of characteristic points S_{1b} , K_{12} , and K_{23} and the relation used to determine the perturbation amplitude. The numbers near each image in the Schlieren pictures of the process given in Appendix 1 are the numbers of the corresponding frames.

Figure 7.3 gives the values of non-dimensional amplitude $\overline{a_{K12}}$ of the interface K_{12} versus the non-dimensional distance $\overline{X_{K12}}$ passed by K_{12} . These data are given for the shock passage from light to heavy gas.

$$\overline{a_{K12}} = \left(\frac{a_{K12}}{a_{K12}^*} - 1 \right) \frac{1}{At}$$

$$\overline{X_{K12}} = \frac{X_{K12}^1}{\lambda}$$

In these variables the $\overline{a_{K12}}$ value is determined by the relation (1) and is given by the straight line in Fig. 7.3. As seen, only for the run No 627B the $\overline{a_{K12}}$ values coincide with the data obtained by (1). The experimental data allows us to note the following.

1. The combination in one plot of the data of different runs but for similar initial conditions indicate the high reproducibility of the data (runs 627B, 620B and 646B correspond to the soft regime, runs 622B and 619B correspond to the hard regime, runs 633B and 637B correspond to the irregular regime.)

2. For $X_{K12} \rightarrow 0$, the $\overline{a_K}$ values tend to zero for all the runs except for 635B and 636B. This indicates that the relation determining the a_K^* is in a good agreement with the experimental data for the soft and hard regimes.

3. The experimental data indicate that when passing from the runs 627B, 620B and 646B to the runs 622B and 619B, and then to the runs 633B, 637B and 634B, we observe the increase of the deviation of the amplitude $\overline{a_k}$ from the value determined by the Richtmyer relation. This deviation of $\overline{a_k}(\overline{X_k})$ is due to the different character of refraction of S_{e1a} on K_{12} .

Comparison of the experimental data for the passage of the incident shock wave from heavy to light gas with the values obtained from the relation suggested by Meyer and Blewett (1972) gives the two-fold excess of the theoretical values of the perturbation growth rate over the experimental values (the calculated and experimental values of da_{K12}/dt are 168 and 75 m/s (run 628B), 153 and 76 m/s (run 631B), and 321 and 156 m/s (run 629B), respectively).

7.2. Evolution of the interface after the interaction with the reflected shock wave.

The experiments with the recording of the interface interaction with the reflected shock were performed to determine the effect of the evolution of the instability on K_{12} on the evolution of the instability on K_{23} (after the interaction with the reflected shock). The main difficulty in solving this problem is due to the fact that by the moment of collision with the reflected shock, the K_{12} is the layer of the thickness Δ comparable to the perturbation amplitude. This results in the reduced perturbation growth rate in comparison with that for the layer of $\Delta=0$. In addition, by the moment of collision with the S_{e2b} , the amplitude of perturbation on K_{12} may be high enough for the soft regime of refraction (for which the relation (1) is true) to change into the hard regime. This phenomenon is also accompanied by the decrease in perturbation growth rate. Taking into account the factors mentioned above, the task of isolating the effect of the pre-history of RMI evolution may be considered rather difficult.

Figure 7.4 gives one of the Schlieren pictures. It shows the interface K_{23} formed after the interaction of K_{12} with S_{e2b} . S_{i2a} is the refracted shock propagating in gas A. This figure shows the characteristic points used for obtaining the quantitative information. The coordinates of these points and the determination of

the measured values are given in Tables (see Appendix 3); the corresponding x-t diagrams are given in Appendix 2.

Table 7.2 gives the processed data for three runs. The experimentally measured perturbation growth rates for K_{12} and K_{23} (column 1 of the table) are compared with the calculated data. The column 2 gives the growth rates calculated from the Richtmyer relation. The column 3 gives the values calculated from the modified Richtmyer relation:

$$\frac{da_K}{dt} = \frac{a_K^* U k A t}{\Psi} \quad (3)$$

The value $\Psi(k, \Delta, At)$ is calculated according to Duff et al. (1962). The modified Richtmyer relation (3) is used to account for the effect of the changing of discontinuous interface into continuous one.

The last two columns give the data on the amplitude growth rate for the perturbation of K_{23} calculated from (2). The calculation was performed twice, first on the assumption that the boundary retains the discontinuous density distribution at all the stages of evolution, i.e. $\Psi=1$ (column 4), then on the assumption that from the second stage, the boundary becomes the continuous interface, and the values Ψ are calculated according to Duff et al. (1962) for experimentally measured Δ values (column 5).

It should be noted the following.

1. Because the first stage of the interaction of the interface with the incident shock wave is complicated by re-phasing, it is impossible to calculate the perturbation growth rate from (1); for calculating the perturbation growth rate at the late stages, we used the da_{K12}/dt obtained in experiment.

2. The values of "compressed" amplitude after the end of refraction of S_{e2b} were taken from x-t diagrams. Then the amplitude growth rate for the perturbation on K_{23} was determined by the relation (2).

Fig. 7.4. Designation of characteristic points on K_{12} . Run No. 639B, frame No. 13. Test section OKM-4. CFV is the center of the field of view (see Fig. 1.2.).

As seen from the data of run 592B (Table 7.2), the experimentally measured amplitude growth rate for perturbation on K_{23} demonstrates a good coincidence with the rate calculated from (2) with account for Ψ according to Duff et al. (1962). The similar comparison of the rates for run No 641B shows that the experimental value is nearly twice as high as the calculated value and within the error coincides with the value calculated from (2) for $\Psi=1$. Because both runs were performed for similar initial conditions, additional tests are required.

The experimental value of the rate in run 639B is far lower than that obtained from the relation (2). This run was performed for the larger Atwood number, and the character of refraction of the reflected shock on the interface may be related to the hard regime. The shape of the shock S_{i2a} (see Appendix 1) testifies to this suggestion. This run cannot be used for comparison with the calculation by (2).

In the run 638B performed with Xe-He gas combination ($At=0.915$), the refraction of the reflected shock was of the irregular character.

In the run 640B the Mach number of the incident shock wave was lower than expected. Because of this, the evolution of instability was recorded only for the interface K_{12} .

The results of experiments allow us to conclude that the interface evolution before the interaction with the reflected shock wave affects the evolution of this interface after the interaction. The quantitative account for this phenomenon requires further investigation.

TABLE 7.2. Results of experiments with the reflected shock.

Run No. 592B Xe $\rightarrow$ Kr, $\lambda = 36$ mm, $a_0 = 5$ mm, $At = 0.182$

	1	2	3	4	5
	Experiment	$a^*k[U]At$	$a^*k[U]At/\Psi$	$da/dt, \Psi=1$	da/dt
K_{12}	0.027				
K_{23}	0.050	0.050	0.032	0.077	0.059

Run No. 641B Xe $\rightarrow$ Kr, $\lambda = 36$ mm, $a_0 = 5$ mm, $At = 0.182$

	1	2	3	4	5
	Experiment	$a^*k[U]At$	$a^*k[u]A/\psi$	$da/dt, \Psi=1$	da/dt
K_{12}	0.028			0	
K_{23}	0.096	0.058		0.086	

Run No. 639B Xe $\rightarrow$ Ar, $\lambda = 36$ mm, $a_0 = 5$ mm, $At = 0.45$

	1	2	3	4	5
	Experiment	$a^*k[U]At$	$a^*k[U]At/\psi$	$da/dt, \Psi=1$	da/dt
K_{12}	0.0804				
K_{23}	0.196	0.363	0.244	0.444	0.324

8. CONCLUSIONS

1. We studied the Richtmyer-Meshkov Instability on the passage of the incident shock wave through the 2D sinusoidal initial interface modeled by a thin film. The results of the experiments include:

- Schlieren pictures of the performed experiments (Appendix 1);
- x-t diagrams of the motion of characteristic points of the interface zone between the compressed flows and the refracted shock waves (Appendix 2);
- tables of the data measured from the Schlieren pictures.

2. We present the data on the RMI evolution induced by the interaction of the reflected shock wave with the 2D sinusoidal interface. Schlieren pictures of the process, x-t diagrams of the motion of characteristic points and the tables of the processed data are given in Appendices 1, 2, and 3, respectively.

The second stage of the studies on the contract will include:

1. Analysis of results on the RMI evolution after the interaction of S_{e1a} with K_0 .
2. Analysis of results on the interaction of the reflected shock with the 2D interface K_{12} . Additional experiments will be performed.
3. Performance of the experiments on the RMI evolution on the shock passage through the 3D interface.

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APPENDIX 1

SCHLIEREN PICTURES

No. 635B, Kr-Xe, OKM-5, $\lambda=36\text{mm}$, $a_0=30\text{mm}$, $M_{e1a}=3.74$

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No. 636B, Kr-Xe, OKM-5, $\lambda=36\text{mm}$, $a_0=30\text{mm}$, $M_{e1a}=3.76$

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No. 620B, Ar-Kr, OKM-4, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e1a}=3.48$

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No. 646B, Ar-Kr, OKM-2M, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e1a}=3.56$

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No. 631B, Xe-Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=4.91$

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No. 629B, Xe-Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e1a}=4.70$

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No. 630B, Xe-Ar, OKM-5, $\lambda=36\text{mm}$, $d\theta=20\text{mm}$, $M_{e1a}=4.50$

No. 632B, Xe-Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=30\text{mm}$, $M_{\text{ela}}=4.57$

No. 622B, He-Xe, OKM-5, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e1a}=2.88$

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No. 637B, He-Xe, OKM-4, $\lambda=36\text{mm}$, $a_0=20\text{mm}$, $M_{e1a}=2.75$

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No. 634B, He-Xe, OKM-5, $\lambda=36\text{mm}$, $a_0=30\text{mm}$, $M_{e1a}=2.78$

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No. 639B, Xe-Ar, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e12}=4.81$

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No. 641B, Xe-Kr, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{\text{ela}}=3.98$

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13

No. 592B, Xe-Kr, OKM-4, $\lambda=36\text{mm}$, $a\theta=5\text{mm}$, $M_{e18}=3.89$

APPENDIX 2

X-T DIAGRAMS OF THE PROCESS

No. 635B, OKM-5, Kr-Xe, $\lambda=36$ mm, $a_0=30$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

$\bullet \bullet \bullet \bullet$ — K_{12}^2
 $\bullet \bullet \bullet \bullet$ — K_{12}^4
 $\circ \circ \circ \circ$ — S_{11b}^1
 $\circ \circ \circ \circ$ — S_{11b}^2

No. 636B, OKM-5, Kr-Xe, OKM-5, $\lambda=36$ mm, $a_0=30$ m.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 627B, OKM-5, Ar-Kr, $\lambda=36$ mm, $a_0=10$ mm.
 X - is counted from the film fastening plane.
 t=0 - time of the first frame

No. 620B, OKM-4, Ar-Kr, $\lambda=36$ mm, $a_0=10$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

$\bullet$ — K_{12}^1
 $\dots$ — K_{12}^4
 $\circ$ — S_{11b}^1

No. 646B, OKM-2M, Ar-Kr, $\lambda=36$ mm, $a_0=10$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 628B, OKM-5, Xe-Ar, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

$\bullet\bullet\bullet\bullet$ — K_{12}^1
 $\bullet\bullet\bullet\bullet$ — K_{12}^3
 $\bullet\bullet\bullet\bullet$ — K_{12}^4
 $\circ\circ\circ\circ$ — S_{11b}^1
 $\circ\circ\circ\circ$ — S_{11b}^2

No. 631B, OKM-5, Xe-Ar, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 629B, OKM-5, Xe-Ar, $\lambda=36$ mm, $a_0=10$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 630B, OKM-5, Xe-Ar, $\lambda=36$ mm, $a_0=20$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 632B, OKM-5, Xe-Ar, $\lambda=36$ mm, $a_0=30$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

$\bullet$ K_{12}^1
 $\circ$ K_{12}^3
 $\bullet$ K_{12}^4
 $\circ$ S_{11b}^1

No. 622B, OKM-5, He-Xe, $\lambda=36\text{mm}$, $a_0=10\text{mm}$,
 X - is counted from the film fastening plane.
 $t=0$ - time of first frame.

No. 619B, OKM-4, He-Xe, $\lambda=36$ mm, $a_0=10$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of first frame.

No. 633B, OKM-5, He-Xe, $\lambda=36$ mm, $a_0=20$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

$\bullet\bullet\bullet\bullet$ — K_{12}^1
 $\bullet\bullet\bullet\bullet$ — K_{12}^4
 $\circ\circ\circ\circ$ — S_{11b}^1
 $\bullet\bullet\bullet\bullet$ — S_{11b}^2

No. 637B, OKM-4, He-Xe, $\lambda=36$ mm, $a_0=20$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

•••••	—	K_{12}^1
•••••	—	K_{12}^4
○ ○ ○ ○ ○	—	S_{11b}^1
•••••	—	S_{11b}^2

No. 634B, OKM-5, He-Xe, $\lambda=36$ mm, $a_0=30$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

$\bullet$ K_{12}^1
 $\cdot$ K_{12}^4
 $\circ$ S_{11b}^1
 $\circ$ S_{11b}^2

No. 638B, OKM-4, Xe-He, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 639B, OKM-4, Xe-Ar, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 640B, OKM-4, Xe-Kr, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 $t=0$ - time of the first frame.

No. 641B, OKM-4, Xe-Kr, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 t=0 - time of the first frame.

No. 592B, OKM-4, Xe-Kr, $\lambda=36$ mm, $a_0=5$ mm.
 X - is counted from the film fastening plane.
 t=0 - time of the first frame.

APPENDIX 3

TABLES OF THE DATA

No. 635B, Kr→Xe, OKM-5, $\lambda=36\text{mm}$, $a_f=30\text{mm}$, $M_{e1a}=3.74$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	X_{K12}^2	$\overline{X}_{K12}^4$	$a_{K12} = \frac{X_{K12}^2 - \overline{X}_{K12}^4}{X_{K12}^2 - \overline{X}_{K12}^4}$	d_1	d_2	h
1	0.00	10.51	6.24	4.27						
2	13.18	18.92	17.50	1.42	15.32					
3	31.01	30.71	32.40	1.69	26.97			11.96		
4	53.68	47.62	48.51	0.89	39.76	11.88	27.88	13.65	22.88	9.08
5	83.55	71.47	70.34	1.13	54.77	26.50	28.27	12.68	26.01	9.64

No. 636B, Kr→Xe, OKM-5, $\lambda=36\text{mm}$, $a_f=30\text{mm}$, $M_{e1a}=3.76$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	X_{K12}^2	$\overline{X}_{K12}^4$	$a_{K12} = \frac{X_{K12}^2 - \overline{X}_{K12}^4}{X_{K12}^2 - \overline{X}_{K12}^4}$	d_1	d_2	h
1	0.00	15.26	11.88	3.38						
2	11.98	20.09	22.23	2.14	18.56					
3	24.39	30.42	32.25	1.83	25.36					
4	38.40	45.92	47.57	1.65	33.06	8.74	24.33	16.42	24.63	8.98
5	52.30	50.35	50.98	0.63	40.44	15.10	25.35	15.47	25.09	11.7
6	70.55	63.90	62.46	1.44	49.76	23.43	26.33	15.24	26.56	9.28
7	91.17	78.59	77.05	1.54	60.85	33.05	27.81	16.95	30.39	9.54
8	101.82	85.68	84.83	0.85	66.15	38.06	28.09	15.92	30.58	7.74
9	116.99	96.06	97.09	1.03	73.84	44.99	28.84	16.73		9.44

No. 627B, Ar→Kr, OKM-5, $\lambda=36\text{mm}$, $a_g=10\text{mm}$, $M_{e1a}=3.67$

No. of frame	t	X_{i1b}^1	X_{K12}^1	X_{K12}^2	$\bar{X}_{K12}^4$	$\Delta = X_{K12}^1 - X_{K12}^2$	$a_{K12} = X_{K12}^2 - \bar{X}_{K12}^4$	d_1	d_2
1	0.00	15.86	13.32	11.61	5.51	1.71	6.10		
2	11.61	26.64	21.84	20.13	9.60	1.71	10.53		
3	24.15	37.47	30.99	29.12	17.50	1.87	11.62	15.56	4.9
4	36.19	48.72	39.66	37.79	24.19	1.87	13.60	15.27	6.06
5	51.49	63.52	50.39	48.08	32.51	2.31	15.57	14.99	7.64
6	70.77	81.64	63.64	61.49	43.80	2.15	17.69	14.02	7.98
7	90.20	99.46	76.08	74.57	55.03	1.51	19.54	10.95	10.26
8	108.28		88.61	87.00	65.89	1.61	21.11	9.71	10.43
9	135.81		108.14	106.85	82.94	1.29	23.91	8.72	11.05

No. 620B, Ar→Kr, OKM-4, $\lambda=36\text{mm}$, $a_g=10\text{mm}$, $M_{e1a}=3.48$

No. of frame	t	X_{i1b}^1	X_{K12}^1	X_{K12}^2	$\bar{X}_{K12}^4$	$\Delta = X_{K12}^1 - X_{K12}^2$	$a_{K12} = X_{K12}^2 - \bar{X}_{K12}^4$	d_1	d_2	h
1	0.00	96.95	74.33		50.36					
2	5.46	102.63	78.20	75.42	54.6	2.78	20.76		1.75	
3	12.10	107.88	83.77	80.99	58.2	2.78	22.73	9.59	6.71	9.53
4	22.49	117.42	89.21	86.54	64.19	2.67	22.30	8.55	11.29	11.48
5	33.83	127.71	96.4	93.89	70.37	2.51	23.45	8.42	12.58	10.17
6	47.13	140.04	105.06	102.74	77.89	2.32	24.80	9.05	14.15	11.45
6	47.13	140.84	105.58	103.43	78.88	2.15	24.49	9.05	13.41	10.34
7	65.24	156.89	116.6	114.50	88.56	2.10	25.87	11.4	13.13	10.40
8	85.37		128.89	126.98	100.09	1.91	26.83	10.78	15.27	9.45
9	109.98		143.6	141.65	112.71	1.95	27.88	9.46	16.28	11.93

No. 646B, Ar→Kr, OKM-2M, $\lambda=36\text{mm}$, $a_g=10\text{mm}$, $M_{e1a}=3.56$

No. of frame	t	X_{i1b}^1	X_{K12}^1	X_{K12}^2	$\bar{X}_{K12}^4$	$\Delta = X_{K12}^1 - X_{K12}^2$	$a_{K12} = X_{K12}^2 - \bar{X}_{K12}^4$	d_2	h
1	0.00	229.9	172.39	170.59	142.11				
2	12.38	240.72	179.81	178.01	150.53	1.80	27.45	27.52	15.78
3	21.03	247.74	183.20	181.49	155.81	1.71	28.11	26.19	13.35
4	33.46	259.06	192.14	190.30	163.44	1.84	26.86	27.21	13.26
5	46.77	272.05	201.10	199.15	172.01	1.95	27.13	27.51	18.08
6	60.21		209.01	207.06	180.44	1.95	27.23	28.5	13.67
7	73.93		218.31	216.29	188.3	2.02	27.98	28.52	15.03
8	90.29		228.41	226.30	198.67	2.11	27.63	27.61	14.73
9	107.71		239.68	237.35	209.27	2.33	28.08	27.54	15.79
109	132.06		255.96	253.61	224.54	2.35	29.06	28.86	15.84

No. 628B, Xe→Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=4.92$

No. of frame	t	X_{i1b}^1	X_{i1b}^2	a_S	$\bar{X}_{K12}^1$	X_{K12}^3	X_{K12}^4	$\Delta = X_{K12}^3 - X_{K12}^4$	$a_{K12} = \bar{X}_{K12}^1 - X_{K12}^3$
1	0.00	25.49	24.25	0.16	16.94	16.29	15.23	1.06	0.65
2	20.81	47.93	47.32	0.08	34.10	31.23	30.58	0.65	2.87
3	36.16	64.41	63.78	0.09	46.59	42.48	41.74	0.94	3.91
4	114.64				109.9	100.13	98.46	1.67	9.77

No. 631B, Xe→Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=4.47$

No. of frame	t	X_{i1b}^1	X_{i1b}^2	a_S	$\bar{X}_{K12}^1$	X_{K12}^3	X_{K12}^4	$\Delta = X_{K12}^3 - X_{K12}^4$	$a_{K12} = \bar{X}_{K12}^1 - X_{K12}^3$
1	0.00	7.93	5.83	2.1					
2	7.78	15.71	14.18	1.53	9.42	8.66	6.73	1.93	0.76
3	15.75	23.49	22.36	1.13	15.61	14.95	13.45	1.50	0.66
4	24.44	32.25	31.25	1.00	22.19	20.97	19.09	1.88	1.22
5	34.89	43.22	42.24	0.98	30.31	27.77	25.82	1.95	2.54
6	45.11	53.85	53.24	0.61	38.11	34.68	32.56	2.12	3.43
7	57.62	66.76	66.39	0.37	48.30	43.48	41.17	2.31	4.83
8	73.65	84.03	83.05	0.98	60.33	54.99	52.04	2.95	5.33
9	91.42	103.12	102.09	1.03	74.17	67.35	64.63	2.72	6.83
10	115.37				91.89	83.34	80.68	2.66	8.54

No. 629B, Xe→Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e1a}=4.7$

No. of frame	t	X_{i1b}^1	X_{i1b}^2	a_S	$\bar{X}_{K12}^1$	X_{K12}^3	X_{K12}^4	$\Delta = X_{K12}^3 - X_{K12}^4$	$a_{K12} = \bar{X}_{K12}^1 - X_{K12}^3$
1	0.0	12.29	9.67	2.62					
2	4.50	25.80	25.02	0.78	17.87	15.82	14.75	1.07	2.05
3	26.68	39.60	38.66	0.94	29.40	24.93	23.23	1.7	4.47
4	40.49	54.30	53.76	0.54	41.41	34.03	32.12	1.91	7.38
5	57.36	72.31	71.63	0.68	55.77	45.62	43.34	2.28	10.15
6	81.81	98.51	98.51	0.00	75.58	62.51	60.01	2.5	13.07
6	81.81	96.47	96.47	0.00	75.29	62.03	59.97	2.06	13.26
7	102.37				99.90	82.27	79.91	2.36	17.63

No. 630B, Xe→Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=20\text{mm}$, $M_{e1a}=4.5$

No. of frame	t	X_{i1b}^1	X_{i1b}^2	a_S	$\bar{X}_{K12}^1$	X_{K12}^3	X_{K12}^4	Δ	$a_{K12} = \bar{X}_{K12}^1 - X_{K12}^3$	d_1	d_2	h
1	0.0	12.23	9.87	2.36								
2	10.18	21.17	19.91	1.26	15.53	10.07			5.45		4.44	
3	23.02	34.13	32.62	1.51	26.22	19.25			6.98		5.29	
4	37.87	48.79	48.40	0.04	38.95	28.41	25.60	2.81	10.54	7.36	6.22	5.74
5	54.89	66.85	65.72	1.13	53.72	38.32	34.47	3.85	15.40	8.83	7.5	5.80
6	75.99	88.43	87.88	0.55	71.68	49.90	47.65	2.25	21.78	10.8	10.12	7.33
7	99.87				91.05	66.80	64.21	2.6	24.25	10.57	11.22	7.79
8	132.76					87.93	84.98	2.95		9.17	14.51	

No. 632B, Xe→Ar, OKM-5, $\lambda=36\text{mm}$, $a_0=30\text{mm}$, $M_{e12}=4.57$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	$\bar{X}_{K12}^1$	X_{K12}^3	$\bar{X}_{K12}^4$	Δ	$a_{K12} = \bar{X}_{K12}^1 - X_{K12}^3$	d_1	d_2	h
1	0.0	15.44	14.31	1.13								
2	9.18	24.73	23.58	1.15	18.06	11.77	9.72	1.8	6.29	5.52	5.52	3.92
3	16.5	32.43	31.81	0.62	24.47	16.69	14.88	1.81	7.79	6.00	7.00	
4	27.41	42.75	42.20	0.55	33.81	22.67	19.87	2.80	11.14	6.01	8.08	6.27
5	42.12	58.13	57.15	0.99	47.16	30.08	27.05	3.02	17.08	6.24	11.99	7.24
6	59.93	76.24	75.14	1.10	62.44	41.13	38.41	2.72	21.34	6.18	12.13	7.84
7	74.13	89.99	89.93	0.61	74.66	49.99	46.97	3.02	24.67	7.86	12.89	9.07
8	87.3	102.96	102.59	0.37	85.94	58.83	56.32	2.51	27.11	8.26	12.63	11.14
9	104.15				99.16	69.85	67.59	2.56	29.31	9.53	13.48	11.10

No. 622B, He→Xe, OKM-5, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e12}=2.88$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	$\bar{X}_{K12}^1$	$\bar{X}_{K12}^4$	$a_{K12} = \bar{X}_{K12}^1 - \bar{X}_{K12}^4$	d_1	d_2	h
1	0.0	54.85			45.16	17.23	27.93	9.06	12.78	8.17
2	6.11	60.68			48.91	19.61	29.31	8.16	9.08	5.85
3	15.82	68.59			54.49	22.82	31.67	9.39	11.78	9.05
4	23.96	74.76			59.04	25.24	33.8	8.90	11.21	9.62
5	31.8	81.95			64.19	28.18	36.01	8.53	14.42	10.24
6	41.97	90.21			69.79	31.95	37.85	8.56	15.26	9.66
7	54.24	100.23			77.19	36.35	40.84	8.60	15.85	9.9
8	65.57				84.08	40.81	43.28	7.95	16.64	10.6
9	78.21				91.46	45.93	45.53	7.08	18.61	11.43
10	89.82				98.53	50.57	47.95	6.68	20.31	11.07
11	104.2				106.94	56.87	50.07	6.70	20.86	10.54
12	122.37				117.73	64.13	53.6	6.36	26.21	12.54

No. 619B, He→Xe, OKM-4, $\lambda=36\text{mm}$, $a_0=10\text{mm}$, $M_{e12}=2.81$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	$\bar{X}_{K12}^1$	$\bar{X}_{K12}^4$	$a_{K12} = \bar{X}_{K12}^1 - \bar{X}_{K12}^4$	d_1	d_2	h
1	0.00	97.47			76.09	35.00	40.00	7.45	17.89	9.01
2	8.96				80.56	39.04	41.53	7.39	18.83	8.68
3	17.40	112.95			85.69	42.32	43.37	9.09	18.61	9.60
4	26.90	121.21			91.77	46.73	45.04	8.47	22.79	9.50
5	35.51	128.76			96.59	50.44	46.15	9.93	21.92	9.71
6	44.05	136.27			102.12	54.58	47.54	9.42	23.50	10.13
7	55.08	146.04			109.09	59.52	49.58	9.73	27.23	12.72
8	66.56	155.76			116.23	64.79	51.42	8.98	28.59	11.54
9	79.66	167.42			124.52	70.29	54.23	10.65	29.83	14.63
10	94.82				133.79	77.23	56.56	12.24	31.84	15.66
11	109.23				143.35	83.81	59.54	10.64	34.03	17.16
12	131.78				157.08	94.76	62.32	11.33	36.00	21.42

No. 633B, He→Xe, OKM-5, $\lambda=36\text{mm}$, $a_f=20\text{mm}$, $M_{e1a}=2.89$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	X_{K12}^1	$\bar{X}_{K12}^4$	$a_{K12} = \frac{X_{K12}^1 - \bar{X}_{K12}^4}{X_{K12}^1 - \bar{X}_{K12}^4}$	d_1	d_2
1	0.00	15.94			14.31				
2	6.80	20.84	12.29	8.55	19.02				
3	14.01	26.72	20.97	5.75	23.19				
4	22.43	33.29	30.31	2.98	31.21				
5	30.11	40.11	38.57	1.54	35.44				24.03
6	40.35	49.32	48.46	0.86	42.18			9.37	26.80
7	48.72	57.30	55.72	1.58	46.93	4.87	42.06	7.87	32.42
8	58.86	66.31	64.74	1.58	54.52	7.58	46.94	6.57	33.17
9	67.73	73.61	72.68	0.93	60.09	10.47	49.62	6.84	
10	78.01	82.33	81.37	0.96	66.4	14.54	51.86	6.45	
11	90.06	92.79	92.13	0.66	73.76	18.75	55.01	6.79	
12	102.41				81.19	24.72		6.58	
13	118.22				91.16	31.44		6.68	
14	137.78					39.39		6.79	
15	170.97					53.57			

No. 637B, He→Xe, OKM-4, $\lambda=36\text{mm}$, $a_f=20\text{mm}$, $M_{e1a}=2.75$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	X_{K12}^1	$\bar{X}_{K12}^4$	$a_{K12} = \frac{X_{K12}^1 - \bar{X}_{K12}^4}{X_{K12}^1 - \bar{X}_{K12}^4}$	d_1
1	0.00	42.27	41.45	0.82	35.53			
2	10.51	52.22	50.79	1.44	42.18			
3	21.55	62.14	60.36	1.78	49.82			
4	32.26	71.40	70.20	1.20	57.02			6.56
5	42.84	79.66	79.01	0.65	63.29			6.08
6	53.11	88.33	87.30	1.03	69.51			6.04
7	64.59	98.06	97.67	0.39	76.48			6.01
8	77.80	109.42	108.79	0.63	84.48			5.77
9	91.72	120.92	119.96	0.96	93.41	32.65	60.76	6.24
10	106.64	133.52	132.87	0.65	102.52	39.14	63.39	5.94
11	124.89	148.91	148.71	0.197	114.16	47.34	66.82	7.98
12	150.58				129.94	58.99	70.95	8.86

No. 634B, He→Xe, OKM-5, $\lambda=36\text{mm}$, $a_f=30\text{mm}$, $M_{e1a}=2.78$

No. of frame	t	X_{ilb}^1	X_{ilb}^2	a_S	X_{K12}^1	$\bar{X}_{K12}^4$	$a_{K12} = \frac{X_{K12}^1 - \bar{X}_{K12}^4}{X_{K12}^1 - \bar{X}_{K12}^4}$	d_1	d_2
1	0.00	8.58			7.84				
2	5.76	13.29			12.09				
3	11.26	17.20			15.59				
4	18.64	22.48	13.57	8.91	19.76				
5	26.41	27.97	22.30	5.67	24.53				
6	35.07	33.94	31.05	2.89	31.17				
7	44.71	42.41	40.88	1.53	37.58			6.45	31.49
8	56.39	52.95	51.65	1.30	44.04			6.42	
9	68.96	64.32	62.17	2.15	51.71			5.91	
10	84.674	76.58	75.98	0.60	60.99	4.672	56.31	5.87	
11	100.66	89.28	88.48	0.80	69.75	10.06	59.69	6.45	
11	100.66	88.32			69.58	9.62	59.98	7.03	
12	124.68	106.51			82.91	19.65	63.26	7.80	
13	168.6				108.25	38.2	70.05	7.91	

No. 638B, Xe→He, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=5.07$

No. of frame	t	X_{i1b}^1	X_{e2b}	X_{K12}^2	X_{K23}^2	X_{K12}^3	X_{K23}^3	X_{K12}^4	X_{K23}^4	$a_{K12} = \frac{X_{K12}^2 - X_{K12}^4}{X_{K12}^2 - X_{K12}^4}$	$a_{K23} = \frac{X_{K23}^2 - X_{K23}^4}{X_{K23}^2 - X_{K23}^4}$	$\Delta_{12} = \frac{X_{K12}^3 - X_{K12}^4}{X_{K12}^3 - X_{K12}^4}$	$\Delta_{23} = \frac{X_{K23}^3 - X_{K23}^4}{X_{K23}^3 - X_{K23}^4}$	$\Delta_{12} = \frac{X_{K12}^1 - X_{K12}^2}{X_{K12}^1 - X_{K12}^2}$
1	0.00	76.46		44.27		42.43		39.70		4.57		2.72		
2	6.66	89.53		51.99		49.12		46.05		5.84		3.06		
3	12.79	101.49		59.46		55.29		51.82		7.64		3.49		2.69
4	21.33	117.89		69.51		64.37		60.74		8.77		3.63		3.08
5	30.22	134.01		79.98		73.18		69.87		10.11		3.31		3.77
6	38.71	150.57		90.21		82.60		78.77		11.44		3.83		4.02
7	48.80			101.76		93.36		89.61		12.15		3.75		4.03
8	58.52		164.76	113.13		103.46		100.31		12.82		3.15		4.10
9	67.15		154.37	123.21		113.24		109.22		13.99		4.02		4.19
10	77.26		142.22	134.98		123.64		119.87		15.11		3.77		4.00
11	89.10				142.23		134.68		131.42		10.81		3.25	
12	102.31				152.17		142.81		139.04		13.13		3.75	

No. 639B, Xe→Ar, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{\text{ela}}=4.81$

No. of frame	t	X_{i1b}^1	X_{e2b}	X_{i2a}	X_{K12}^2	X_{K23}^2	X_{K12}^4	X_{K23}^4	$a_{K12} = \frac{X_{K12}^2 - X_{K12}^4}{X_{K12}^2 - X_{K12}^4}$	$a_{K23} = \frac{X_{K23}^2 - X_{K23}^4}{X_{K23}^2 - X_{K23}^4}$
1	0.00	108.90			75.33		67.87		7.46	
2	7.31	117.24			81.29		73.29		8.00	
3	15.09	126.08			87.54		79.24		8.30	
4	22.91	134.94			93.83		85.45		8.38	
5	31.05	144.12			101.12		91.54		9.58	
6	38.34	152.70			107.40		96.87		10.53	
7	46.14	162.01			113.98		102.78		11.20	
8	55.44				121.60		109.96		11.64	
9	64.89		169.98		129.53		117.07		12.46	
9	64.89		170.43		128.87		116.57		12.30	
10	77.06		162.68		138.70		125.23		13.47	
11	92.34			153.80	150.56		136.58			
12	108.47			145.31		155.15		146.10		9.05
13	128.78			142.87		160.48		147.45		13.03

No. 639B, Xe→Ar, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=4.81$

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XY
No. of frame	t	X_{11b}^1	X_{e2b}	X_{12a}	X_{K12}^{5-6}	X_{K23}^{5-6}	X_{K12}^{1-2}	X_{K23}^{1-2}	X_{K12}^{3-4}	X_{K23}^{3-4}	$a_{K12}=YIII-X$	$a_{K23}=IX-XI$	$a_{K12}=XI-X$	$a_{K23}=YII-XI$
1	0.00	108.90			78.70		77.13		69.55		7.58		9.15	
2	7.31	117.24			84.91		83.31		75.43		7.88		9.48	
3	15.09	126.08			91.10		89.61		81.55		8.06		9.55	
4	22.91	134.94			97.58		96.11		87.90		8.21		9.68	
5	31.05	144.12			104.20		102.92		93.89		9.03		10.31	
6	38.34	152.70			109.93		109.14		99.02		10.12		10.91	
7	46.14	162.01			116.49		115.90		105.05		10.85		11.44	
8	55.44				124.23		123.37		112.38		10.99		11.85	
9	64.89		169.98		130.72		131.18		119.16		11.88		12.41	
9	64.89		170.43		131.88		131.35		119.47					
10	77.06		162.68			140.72		140.34		127.72		12.62		13.00
11	92.34		153.80			153.38		153.46		138.96		14.50		14.42
12	108.47			145.31		157.42		157.22		147.84		9.38		9.58
13	128.78			142.87		163.31		163.03		149.37		13.66		13.94

No. 640B, Xe→Kr, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=4.04$

I	II	III	IV	V	VI	VII	VIII	IX
No. of frame	i	X_{i1b}^1	X_{e2b}	X_{K12}^5	X_{K12}^4	X_{K12}^{5-6}	X_{K12}^{3-4}	a_{K12} =VII-VIII
1	0.00	69.85		49.09	44.37	47.46	46.25	1.21
2	6.96	74.60		53.27	48.33	52.04	50.19	1.84
3	15.07	81.32		58.17	52.64	56.72	54.67	2.04
4	22.99	87.67		63.00	57.19	61.27	59.00	2.26
5	32.51	95.70		68.60	62.56	66.94	64.51	2.44
6	42.31	103.75		73.46	67.93	72.13	70.05	2.09
7	50.94	110.90		78.49	72.59	77.10	74.51	2.59
8	60.71	118.85		84.58	78.15	82.85	80.24	2.61
9	71.49	127.06		89.82	82.50	88.09	84.47	3.63
9	83.53	136.62		96.65	88.82	94.82	90.91	3.91
10	96.74	146.54		103.91	96.21	102.03	100.00	3.88
11	114.66	160.18		113.80	105.16	111.95	107.44	4.51
12	139.89			128.34	118.39	126.16	120.68	5.48
13	177.1		154.75	149.12	139.09	147.24	141.33	5.92

No. 641B, Xe→Kr, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{\text{ela}}=3.98$

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XY	XYI	XYII	XYIII	XIX
No.of frame	t	X_{e2b}	X_{i2a}	X_{K12}^{1-2}	X_{K23}^{1-2}	X_{K34}^{1-2}	X_{K12}^{3-4}	X_{K23}^{3-4}	X_{K34}^{3-4}	X_{K12}^{5-6}	X_{K23}^{5-6}	X_{K34}^{5-6}	a_{K12} = Y-VIII	a_{K23} = YI-IX	a_{K34} = YII-X	a_{K12} = XI-VIII	a_{K23} = XII-IX	a_{K34} = XIII-X
1	0.00	169.59		130.30			124.50			128.72			5.80			4.21		
2	6.99	166.93		134.36			128.44			133.11			5.92			4.66		
3	14.21	163.71		138.41			132.36			137.21			6.05			4.85		
4	21.13	160.66		142.52			136.13			140.85			6.39			4.72		
5	27.75	157.98		146.40			139.62			144.67			6.78			5.08		
6	36.23	153.86					144.59			149.34								
6	36.23	152.81		150.89			144.24			149.57			6.65			5.33		
7	45.55	152.56																
8	57.50		145.44		154.04			150.39			153.33			3.65			2.94	
9	69.45		143.33		155.10			150.52			154.54			4.58			4.02	
10	83.84		139.41		156.90			150.73			156.35			6.17			5.62	
11	98.93		134.01			158.04		151.77				157.85		6.27			6.08	
12	120.34		127.19			159.54			151.79			158.81			7.75			7.02
13	168.83		111.74			162.09			153.16			161.55			8.93			8.37

No. 592B, Xe→Kr, OKM-4, $\lambda=36\text{mm}$, $a_0=5\text{mm}$, $M_{e1a}=3.89$

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XY	XYI
No. of frame	t	X_{i1b}^1	X_{e2b}	X_{i2a}	X_{i2b}	X_{K12}^{1-2}	X_{K23}^{1-2}	X_{K34}^{1-2}	X_{K12}^{3-4}	X_{K23}^{3-4}	X_{K34}^{3-4}	$a_{K12}=VII-X$	$a_{K23}=VIII-XI$	$a_{K34}=IX-XII$	Δ_{12}
1	0.00	156.30				108.58			103.89			4.69			3.84
2	4.64	159.73				109.00			105.88			3.12			3.44
3	10.40	164.03				114.15			108.97			5.18			3.66
4	21.51					119.87			114.92			4.95			3.98
5	34.12		169.761			126.65			121.13			5.52			4.60
6	47.59		163.98.			133.71			127.85			5.86			3.87
5	34.12		169.99			126.69			120.93			5.77			4.33
6	47.59		164.08			133.97			128.08			5.92			3.82
7	59.57		159.68			139.90			134.12			5.77			4.55
8	69.38		155.39			145.10			139.10			6.01			5.17
9	79.68		151.27												4.87
10	91.60			145.97											Δ_{23}
11	106.79			141.60	164.81		153.91			150.29			3.62		4.27
12	123.67			136.62	171.37		155.84			151.31			4.54		5.75
13	146.82			129.65			158.01			152.39			5.62		Δ_{34}
14	188.43			116.20				161.36			154.20			7.16	8.82